From the RCPSP to the DRCMPSP: Methodological foundations

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***Abstract*— In this paper we review different approaches for scheduling projects in multi-project environments. We show the evolution of the methodologies from the Resource Constrained Project Scheduling Problem to the Decentralized Resource Constrained Multi-Project Scheduling Problem.**

We argue that traditional methods used in project scheduling cannot cope with the complexity of current real portfolios performed by project-based organizations. We advocate that a decentralized approach can help project managers to deal with complex restrictions and objectives, including not only operational constraints, but also financial and strategic issues. We model complex portfolios as Multi-Agent System, so that we can include complex behavior and restrictions.

Keywords*— *RCPSP; Resource-Constrained Project Scheduling Problem; RCMPSP;Resource-Constrained Multi-Project Scheduling Problem

I. INTRODUCTION

In practice, firms always run several projects at the same time. Therefore, firms have to schedule a set of projects (project portfolio) where some resources (human, machines, facilities, etc.) are shared by several projects.

For this reason, researchers and academics in the area of Project Management and Project Portfolio Management have focussed their attention on solving the Resource Constraint Multi-Project Scheduling Problem (RCMPSP). The problem is an extension of the classical Resource Constrained Project Scheduling Problem (RCPSP) to multi-project environments.

But in a competitive and global word, the complexity of project portfolios is continually increasing, especially for project-based organizations engaged in multi projects at different geographical locations.

For instance, in real projects, some resources are shared by several projects, while others resources are assigned only to a particular project at a time. Some trade-offs between project objectives and global portfolio objectives must be fulfilled. The hypothesis of "renewable resource" cannot be applied in some real cases. Financial constraints and objectives have to be included within the problem. And decisions about project priority (and project selection) have to be aligned with corporate strategy.

Although the initial RCMPSP approach has been extended to cope with this complexity, in practice, some real restrictions are difficult to model under the classical approach. And, on the other side, when it is possible to model the problem, usually it is hard to find a solution.

In order to cope with the complexity of real portfolios, we advocate for decentralized computational methods, as they allow to model multi-project environments from a "bottom-up" approach, where particular constrains can be easily modelled. In particular, we model multi-project environments as a combinational problem.

In this paper, we review the different approaches to multi-project scheduling from the initial RCPSP to the more recent computational methods used in the Decentralized Resource Constrained Multi-Project Scheduling Problem (DRCMPSP). We show the main characteristics of the decentralized approach that we implement by means of multi-agent technologies.

II. THE BASIC APPROACHES TO PROJECT SCHEDULING.

In figure 1, we show an historical overview of project and multi-project scheduling from the XX Century. Early tools where mainly graph based methodologies (Gantt charts[1], [2], Harmonygraph [3], Flow-line scheduling, Lines of balance methods [4], [5], Milestone charts, etc.). During the fifties, researchers developed the mainstream methods based on Graph Theory (PERT [6], CPM [7], ROY [8], PEP [9], PDM [10]). Currently, those methods are still widely used, and they have been implemented in most common project management software. RCPSP was first formulated during the sixties and both mathematical and heuristics methods where developed. The first methods, mainly based on linear programming techniques (*Simplex Method*, *Explicit* or *Implicit Enumeration Methods*, such as *"Branch&Bound"*, etc.) [21]–[23]) could not deal with more complex real constraints and, therefore, heuristics methods became more appropriate.

During the eighties, the multi-project problem became interesting for researchers and academics. We have to wait until de current century to see decentralized approaches.

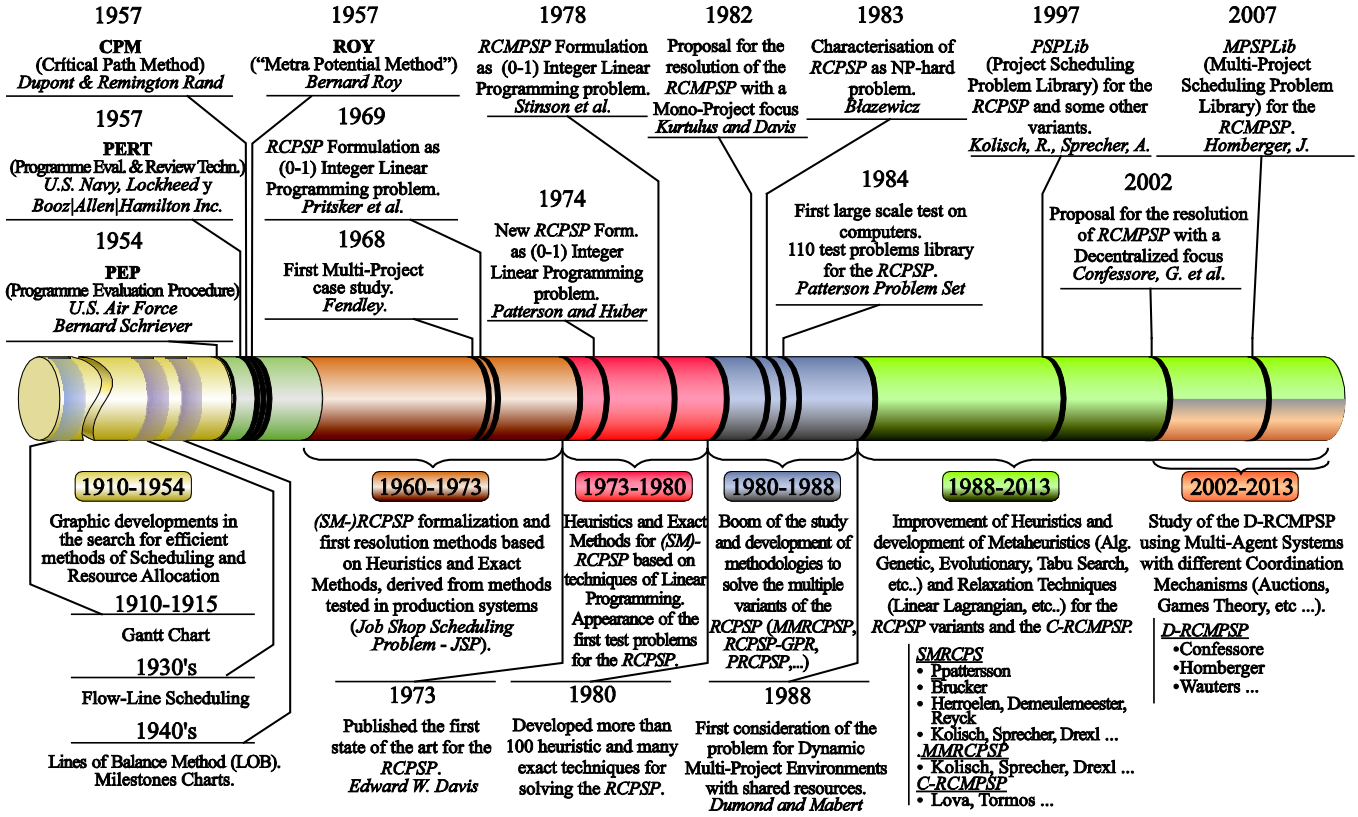

Fig. 1. Timeline with the stages and most important milestones in the study of project scheduling problems with time and resource constrains.

III. MULTI-PROJECT SCHEDULING WITH CONSTRAINTS (RCMPSP)

The *Resource-Constrained Multi-Project Scheduling Problem*", commonly call by the acronym RCMPSP [27], [28] has been widely used to model multi-project environments.

Most of the frameworks distinguish between "local resources" (allocated to a particular project) and "global resources", which can be allocated to all the projects belonging tothe portfolio.

Usually, global resources are human resources with specific high performance competences (i.,e.. Expert engineers) or expensive physical assets with a particular purpose. Firms are not interested in having "excess capacity" of these kind or resources, especially in the short term. On the other side, firms can address more projects by sharing global resources.

Common objective functions are: Minimizing the total duration of the whole portfolio (total makespan); minimizing the average project duration (average makespan); minimizing average project delay or the standard deviation of the project delays. Other firms are more interested in reducing global resources idleness or optimizing the amount of global resources in order to address the highest number of projects.

The solution of the problem shows the schedule of all the projects and the resources needed by each activity.

For simple cases (simple precedence relations, few activities, low number of global resources, etc.), classical Operations Research methods can be used [22] (*Simplex Method*, *Explicit* or *Implicit Enumeration Methods*, such as *Branch&Bound"*, etc.).

More complex problems can be dealt with methodologies like Heuristics, Metaheuristics, Genetic Algorithms, Evolutionary Algorithms, Taboo Search, Ant Colony Algorithms, Simulated Annealing, etc. [30], [31].

A first approach to solve the problem is the Centralized one (CRCMPSP), where all the activities of each project are considered as activities of a global "macro-project" ([30], [32], see fig. 2). The original precedence relations are translated into the global project and two dummy activities are added: One for the beginning and other for the finish of the "macro-project".

The CRCMPSP resolution methods are just extensions of the traditional methods used for solving the simple RCPSP, and they work reasonably well for objective functions like total makespan or resource levelling optimization.

The basic approach can be improved by means of multi-step methodologies. For instance, it is possible to use the feasible schedules obtained in a first step and then apply enhancement algorithms to accommodate particular objectives of individual projects (without losing global feasibility).

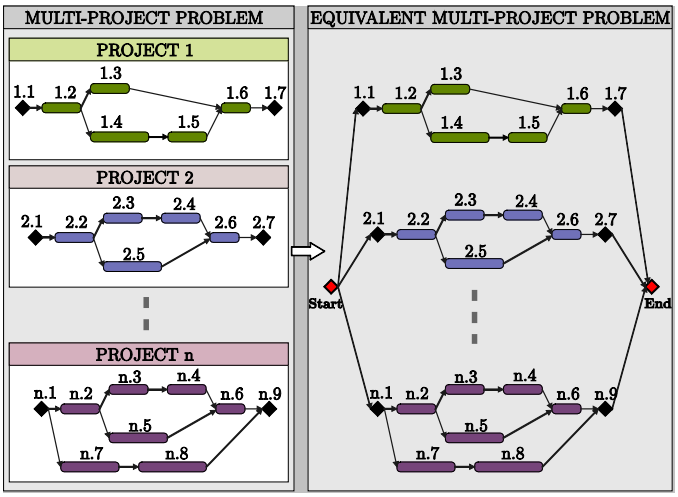

Fig. 2. Conceptual description of the RCMPSP centralized approach.

Anyway, in the centralized approach, there is only a "single programming entity" with all the decision making power. This entity creates a global schedule satisfying global objectives, regardless of possible local particular targets.

IV. The Decentralized Approach to the Resource-Constrained Multi-Project Scheduling Problem (DRCMPSP)

Project based firms are used to manage simultaneously several projects, sometimes in different geographical locations. Each project has its own constraints, customers (internal or external to the firm), stakeholders, etc. In practice, there are overruns and the project manager has to take decisions with local information. At the same time, all the projects should be aligned with corporate strategy. In other words, it makes no sense to develop a project which does not contribute to corporate strategy and financial objectives. In order to include all these issues into the model, real portfolio management demands decentralized methodologies.

The limitations observed by researchers for the centralized approach to the RCMPSP are the origin of the proposal and recent adoption of a new perspective to solve the RCMPSP. It's known as the *Decentralized Resource-Constrained Multi-Project Scheduling Problem* (DRCMPSP) [33].

The term decentralized comes from the fact that these methodologies provide some freedom to individual projects in order to take its own scheduling decisions. Now, the decision-making capacity is distributed among all projects. Therefore, it is required a coordinating entity to organize, arbitrate and check the overall feasibility of the schedules proposed by each project.

The methodology also requires to establish information and communication flows between the coordinating entity (the program or portfolio management) and the project managers (each one managing a particular project). Additionally, it is also possible to include entities acting as *resource managers*, which decide about the process of resources allocation.

In figure 3, we show a picture with the agents of the system. Project manager entities (of individual projects) are responsible for individual project scheduling. One or more Resource Manager entities are engaged in managing the availability of resources.

Above them and in a tactical level, the *Project Portfolio Manager* entity aligns the objectives of each project manager with the objectives of the portoflio. Depending on the context, it can assume roles of coordinating or programming entity.

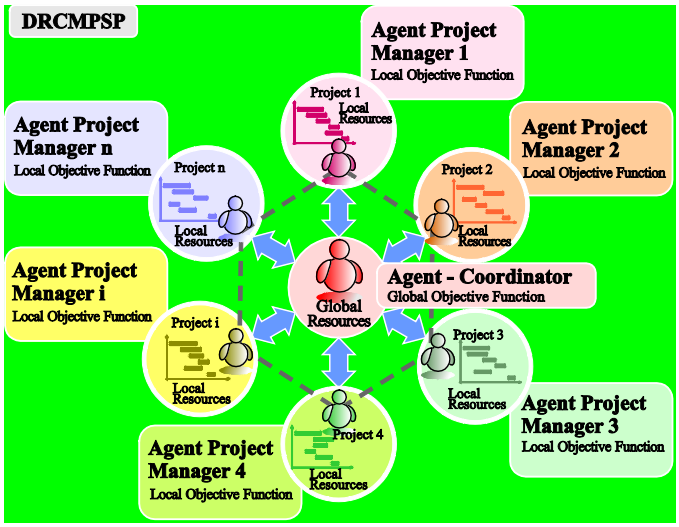

Fig. 3. Conceptual description of the RCMPSP decentralized approach.

The Project Manager entities may contribute to build their initial schedules, but the final decision concerning the best global schedule for all the projects belongs to the Project Portfolio Manager.

A. Coordination Mechanism in DRCMPSP

There are many ways to implement coordination mechanisms among projects, including some methods inspired by other sciences, such as economics, political science and some methodologies used in distributed allocation and decision making systems.

For example, some researchers propose mechanisms that emulate the operation of economic institutions used in the goods and services markets, especially those based on allocation by auctions [33], [34]. Each unit of resource available on a different moment (*slot resource)* is a good, which can be traded in an auction. Project managers bid in the auction in order to take the slot resources they need to fulfil the activities of the project.

Among the different types of auctions (English, Dutch, etc...), Combinational Auctions (CA) seem to be the ones providing better results [35], [36]. It is a kind of multi-item auction that allows the bidders to submit bids not only for each individual auctioned item, but also allows to bid simultaneously for combination of items.

Within the metaphor of combinational auctions, the individual project managers bid for slot-resource combinations that allow them to complete the activities of the project according to the precedence relations.

Other interesting decentralized allocation mechanisms apply Game Theory [37], or Voting Systems [38].

B. Multi-Agent Systems

The computational implementation of most of these decentralized mechanisms use the *Multi-Agent Systems* paradigm [39], [40].

A *Multi-Agent System* (MAS) is a system composed of multiple entities known as agents. These agents are endowed, to a greater or lesser extent, with some kind of individual intelligence and some level of autonomy in their decision-making. The agents also have the possibility of establish some level of communications and interactions between them and with the environment around them.

MAS are *Distributed Artificial Intelligence* (DAI) systems, usually network implemented, where the combined behaviour of their elements can produce a smart result although their individual behaviours can be simple. For this reasons, multi-agent system are particularly suitable for implementing a computational methodology to solve the RCMPSP with a decentralized approach.

In computational terms, each agent would be an independent process of the software system, which exists within a certain context or environment, and with a pattern of more or less self-interested behaviour. This behaviour is usually defined through rules of own performance and responsiveness to external *stimuli*, as simple as possible. In addition, agents can interact following some predefined *agent-agent* and *agent-environment* communication protocols. The environment is usually materialized in form of parameterized scenarios.

Following with the analogy explained in figure 3., we can model the DRCMPSP by means of a *Multi-Agent System* with the following agents:

- The "*Project Manager Agents*", who are responsible for planning the activities of their projects (operational level).
- They may also exist at the operational level, the "*Resource Manager Agents*", who are responsible for managing the availability of resources. They can take decisions in the resource allocation process.
- Above them lie the "*Project Portfolio Manager Agent*", sometimes called simply the Coordinator Agent. It works at a tactical level, trying to align the objectives of the other agents with the objectives of the Organization. It can may assume roles of *coordinator entity* or *programming entity* depending on context.
- Some methods include "*Activity Agents*" or "*Task Agents*", which represent each of the activities of each project, and the "Resource Agents", which represent each of the existing resources.

The Project Manager agents are focussed on developing an optimal (or at least feasible) schedule for their project, based on their goals (objective functions). We need to define how project manager agents interact with other agents and with the environment (in case of modification of scenarios, data requests, coordination possibilities, etc...).

At an operational level, each *Project Manager Agent* is programmed to solve a RCPSP problem, usually using one of the well-proven methodologies to solve this problem (Heuristics, Genetic Algorithms, etc...). The difference now is that the availability of resources to schedule their project is not a fixed data from the beginning, because it can be modified externally through the coordination mechanism.

In some cases, the assigned resource availability should be notified explicitly to each *Agent Project Manager*. In other cases it will be a common information available more or less explicitly or implicitly for all agents.

Moreover, there must be a communication channel that allows the *Project Portfolio Manager Agent* to have feedback and determine the global status of the projects schedules, and thus to know which ones met their local goals. Therefore, communication mechanisms and information flows have to be properly defined during the system modelling phase.

C. Iterative Improvement Processes

Generally, the decentralized resolution methods are performed as an iterative improvement processes. After each iteration with unsatisfactory results, the process is repeated until satisfactory results are achieved (if this is possible). In some methods, the *Coordinator Agent* explores a different allocation of resources between projects for the next iteration, and then the *Project Managers Agents* have to check if they are able to perform a feasible schedule with the new distribution of resources

In other methods, the *Project Management Agents* are "*forced to*" rebuild their schedules. For example, to adjust them to their available budgets due to the change of the resources prices. This creates a new different profile of resource consumption for each project, which must be studied jointly by the *Coordinator Agent*, in order to verify its compatibility with the total availability of resources.

In both cases, the process continues until a satisfactory solution for all parties is reached. Obviously, the process could continue for an indeterminate manner in time, so it is needwe need to include some stop algorithms. For example, after a particular number of interactions without significant improvement or after a maximum computational time.

D. "Acceptably Good" solutions

As mentioned above, these methods cannot guarantee that the best solution obtained is a global optimum of the problem. Usually, the method will provide an "acceptably good" solution (or solutions), close enough to the optimal solution. In practice, the deviations from optimal levels are small, and therefore, the methodology allow multi-project schedules in a reasonable time. This is especially important for large and complex project portfolios, with projects concerning hundreds of activities.

V. Conclusions

We have reviewed the different approaches to multi-project scheduling from the initial RCPSP framework to the decentralized approaches (DRCMPSP). We advocate for a decentralized approach to deal with the complex constraints of real project portfolios. In particular, we model complex project portfolios by means of a combinational auctions and we use multi-agent methodologies to implement the system.

By means of this framework, we can model not only operational constraints, but also financial and strategic issues.

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